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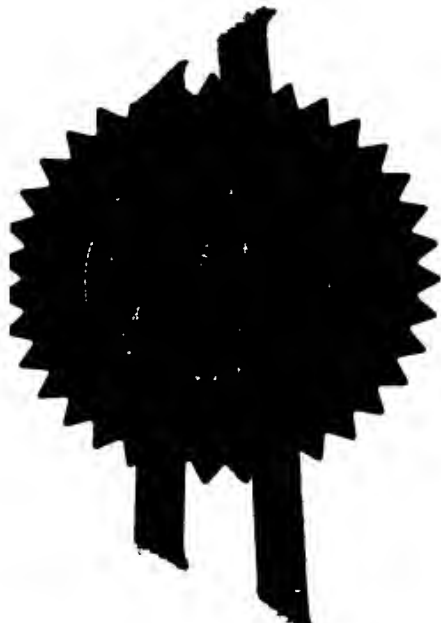
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5 Julianaplein
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4. Title of the invention   Downhole Instrumentation and Cleaning System

5. Name of your agent *(if you have one)*   MIRZA, Akram Karim

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Downhole Instrumentation and Cleaning System

This invention relates to apparatus and methods for making
measurements in a wellbore and operating downhole sensors and
5 other wellbore equipment. Particularly, the invention relates to
such apparatus and methods for sensing and removing solid
deposits.

BACKGROUND OF THE INVENTION

10

The formation of both organic(1) and inorganic(2,3) deposits in
the near wellbore region of producing formations and on the
tubing of a producing hydrocarbon well can be a major and costly
problem. The deposits can seriously impede the productivity of
15 wells by reducing the near wellbore permeability of producing
formations and progressively restrict the diameter of the
tubing.

The formation of inorganic deposits, or scale, is caused by the
20 precipitation of inorganic salts from produced water(2). Calcium
carbonate scale is usually formed by the change in the pressure
and temperature of the produced water in the near wellbore and
in the production tubing. Barium, strontium and calcium sulphate
scales are usually formed by the mixing of formation water and
25 seawater injected into producing wells; the high concentration
of sulphate in seawater mixes with the high concentrations of
divalent cations in formation waters with the resulting
precipitation of the sulphate salts. The formation of scale may
be partly prevented by water shut-off treatments and the use of
30 scale inhibitors. Once formed, scale can be removed only with
some difficulty; calcium carbonate scale can be dissolved by
mineral acids and barite scale can be removed by milling or
scale dissolvers such as EDTA(4). In extreme cases the
production tubing must be removed and replaced, although the

presence of radioactive scale (due to the presence of radium salts) can make scale disposal an environmental issue.

5   The production of hydrocarbons frequently causes the precipitation of organic precipitates such as paraffin waxes and asphaltenes. These organic precipitates are caused by changes in the pressure and temperature of the produced fluids in the near wellbore. The precipitates can be removed with solvent washes (1), although the disposal of the solvent after cleaning
10   represents an increasing environmental problem.

       The solubility of various inorganic and organic species can be predicted from thermodynamic models of the electrolyte solutions or hydrocarbons (5). However, thermodynamic models are
15   essentially equilibrium models and they cannot predict any details of the precipitation process such as the location of precipitation, the rate of precipitation or the degree of supersaturation that the fluid can tolerate.

20   It is an object of this invention to describe an apparatus that can be placed at various locations in a producing hydrocarbon well to measure the deposition of scale and other wellbore deposits and preferably to remove such deposits.

25   PRIOR ART

       Several patents and papers have described both acoustic and non-acoustic methods for sensing the formation of scale in producing hydrocarbon wells and similar environments. Lester(6) described
30   an acoustic method for measuring the thickness of metal oxide corrosion products on the inside of boiler tubes. The thickness of oxide scale is determined by the time of flight of an acoustic pulse applied from the external surface of the pipe. The frequency of the acoustic pulse was 50 MHz, which enabled a
35   scale thickness of approximately 0.1 mm to be detected. Okabe et

al.(7) have described the use of an automated ultrasonic inspection system for determining the thickness of scale formation which has formed on the inside of heat transfer tubes in boilers. A rotating transducer was inserted into the tubes

5   and their diameter as a function of location determined by the reflection of sound from the scale-water interface. O'Sullivan and Allen(8) have used an acoustic wireline logging tool, Schlumberger's Cement Evaluation Tool (CET), to determine the accumulation of scale on the casing of geothermal wells. The

10   interfaces between the scale and wellbore fluid and the scale and the casing are determined by the transit time of the acoustic waves, which have a frequency of approximately 0.5 MHz. Buttram et al.(9) disclosed a method for determining the thickness of scale on the inside of a water pipe by the

15   attentuation of acoustic energy emitted and received by a transducer on the outside of the pipe. The optimum frequency range for the ultrasound was observed to be 3-7 MHz. For example, measurements made using ultrasound below a frequency of 3 MHz gave poor sensitivity to scale thickness and beam

20   spreading was observed to be a problem. Gunarathne and Keatch(10,11) have described an acoustic method of identifying scale types and scale thickness in oil pipelines using the attenuation in the reflected acoustic signal from a tool that is moved through the inside of the pipe. The frequency of the

25   ultrasound used was in the range 3.5-5.0 MHz, which allowed the thickness of barium sulphate scale on steel to be measured to an accuracy of ±0.5 mm.

Spates et al.(12) have described several acoustic-wave devices
30   for determining the deposition of organic precipitates, such as paraffin wax, on to a sensing surface immersed in a petroleum-based fluid. The acoustic measurements were made with devices using various acoustic modes: surface acoustic waves and thickness shear, acoustic plate and flexural plate modes. The
35   devices measured changes in the damping voltage and resonant

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frequency of the device as the wax precipitate formed, although
no details were disclosed regarding the operating frequencies of
the acoustic devices or the acoustic power they generated.
Spates *et al.*(12) discussed periodic cleaning of the sensing
5   surface of the acoustic device by heating the surface to melt
the paraffin wax. The use of acoustic energy to clean the
organic precipitates from the acoustic sensor was not discussed.
Several applications of the measurement of wax accumulation were
described, including location of acoustic devices on the sea
10 floor to monitor the production of hydrocarbon from oil wells
and guide well treatments. Granstaff and Martin(13) described
the application of a quartz microbalance to measure
simultaneously mass loading and liquid properties. The authors
used changes in the resonant frequency and magnitude of the
15 maximum admittance of a quartz microbalance to differentiate
between changes in the mass of material deposited from a liquid
and changes in the properties of the liquid (density and
viscosity). The operating frequency of the quartz microbalance
was close to 5 MHz, at which value the resonator was able to
20 detect solid films of the order of 0.1 μm in thickness.

Kraus *et al.*(14) have disclosed the application of an on-line
quartz crystal microbalance to monitor and control the formation
of organic and inorganic precipitates from hydrocarbons and
25 water. The quartz crystal microbalance consisted of a thickness-
shear mode resonator and was described by Kraus *et al.* as being
substantially similar to those disclosed by Granstaff and
Martin(13). Kraus *et al.* described the use of the thickness-
shear mode resonator for the on-line measurement of scaling,
30 corrosion and biofouling in industrial processes. They also
described the use of the measurement of deposit formation to
determine the treatment required to correct the industrial
process and prevent continual deposit formation, e.g., by use of
a chemical additive such as an inorganic scale inhibitor.
35 Although Kraus *et al.* described the use of a thickness-shear

mode resonator to monitor deposit formation from hydrocarbons, industrial water and their mixtures (including emulsions), no specific reference was made to the operation of these sensors in producing hydrocarbon wells, on either a temporary or permanent

5   basis. No specific reference was made to the treatment of producing hydrocarbon wells, for either organic or inorganic deposit formation, on the basis of measurements made by these sensors.

10   Sivaraman and coworkers(15,16) have developed a laboratory acoustic resonance technique to determine the onset of the precipitation of wax and asphaltene from produced hydrocarbons. The spectrum of resonant frequencies of a sample of liquid hydrocarbon in a cylinder of fixed length and cross-sectional

15   area was obtained as a function of temperature and pressure. The resonant spectra were collected using two ultrasonic transducers operating over the frequency range 0-40 kHz, although significant resonances were observed only over the frequency range 5-35 kHz. The precipitation of wax and/or asphaltene from

20   the liquid hydrocarbon sample as the pressure and temperature of the sample was changes resulted in changes in the frequency of the resonances and changes in their amplitude. The changes in the resonant spectra were attributed to changes velocity of sound in the liquid. No reference was made to the precipitation

25   of wax or asphaltene on the transmitting or receiving transducer.

Emmons and Jordan(17) have described the use of a thickness-shear mode resonator to monitor the formation of barium sulphate

30   in samples of produced water collected at the well head. The resonator was immersed in a fixed volume of produced water and known amounts of soluble barium ions were added to precipitate barium sulphate scale. The resonator detected the formation of scale on its sensing surface by a decrease in resonant

35   frequency. The amount of barium added before scale formation was

detected by the resonator gave an indication of the level of inhibition in the produced water. Emmons and Jordan argued that the formation of scale by small additions of barium ions indicated the produced water was close to scaling and treatment
5 of the well by a suitable scale inhibitor was required. Note that this method of monitoring scale formation is not an *in situ* method and does not measure the spontaneous formation of scale under downhole conditions of temperature, pressure, composition and flow. In addition, the resonator was not able to clean the
10 scale from its sensing surface. Gabrielli et al.(18) have used a quartz crystal microbalance to monitor the formation of calcium carbonate scale under laboratory conditions. The resonant frequency of the microbalance was 6 MHz and calcium carbonate deposition rates of 200-400 $\mu g/cm^2$ per hour were measured. The
15 calcium carbonate scale was observed to be the mineral calcite, which, with an assumed density of 2.71 g/cm^3, gave deposits of 0.7-1.5 μm in thickness. The rate of scale accumulation measured by the quartz microbalance was compared with a standard electrochemical scale monitor that measured the redox current
20 passing through an electrode as water was reduced. The decline in redox current gave an indirect measure of the decrease in the surface area of the electrode as it was covered with scale and was observed to be less sensitive to scale formation than the quartz crystal microbalance. Nohata and Taguchi(19) have
25 described the use of a piezoelectric quartz crystal to monitor the fouling of surfaces in a water cooling tower by inorganic scale and bacterial growth at ambient conditions. Although Nohata and Taguchi did not specifically disclose the operating frequency of the quartz crystal, a value of about 5 MHz can be
30 deduced from the measured accumulation rates of 1-20 $\mu g/cm^2$ per day.

Non-acoustic scale sensing techniques have also been reported. Slough(20) described a method of determining the accumulation of
35 scale in petroleum pipelines using a heat transfer sensor. The

scale formed on the external wall of the sensor impeded the loss of heat from a heating element in the sensor to the fluid flowing in the pipeline. The decrease in heat flow was measured by means of a temperature sensor. Sneider(21) has described a
5 wellbore scale monitor that measured the radioactivity of the radium salts precipitated with other alkaline earth metal salts. Sneider proposed to use the measurements of scale radioactivity to indicate when and where the placement of scale inhibitor was required. A somewhat similar scale monitoring technique has been
10 proposed by Carroll and Scott(22); the radioactivity of the scale was detected by a wireline gamma ray detector, correcting for the natural gamma radiation emitted from the surrounding rock formations.

15 Stock(23) used accurately measured pressure drops over various sections of a reinjection pipeline in a geothermal power plant to monitor the growth of silica scale. The measured pressure drops across the sections of pipe produced friction factors in the range 0.1-0.2, compared to an expected value of 0.01.
20 Cleaning the silica scale from the pipeline sections using a wire brush pig resulted in the friction factor dropping below a value of 0.06. The company Oilfield Production Analysts Ltd.(24) currently produce both laboratory and field systems to evaluate the scaling potential of oilfield brine samples by monitoring
25 the pressure drop across a capillary tube through which the brine flows and deposits scale. Flemming et al.(25) described three optical techniques to monitor fouling in industrial process systems. The techniques consisted of measurement of the intensity of light reflected from a small optical fibre probe,
30 the measurement of turbidity through optical windows in a flow line (using periodically cleaned windows in the flow line as a reference optical pathlength) and an infrared spectroscopy flow cell. The accumulation of deposits and the chemical nature of the deposits on the optical windows of the infrared flow cell
35 could be determined from the infrared spectra.

A number of published reports have described the application of sonic energy for cleaning producing oil wells and equipment in similar industrial processes. Keenan(26) disclosed a method of

5 cleaning downhole deposits, such as tar, from producing formations and production tubing. Keenan gave no details of the power or frequency of the sound used for wellbore cleaning. Bodine(27) has described a low frequency (20-100 Hz) vibrating device for cleaning deposits on the walls of casing and tubing

10 and in formations and gravel packs. The vibrations were generated in the device by an orbiting mass on an unbalanced rotor, which, in turn, produced a whirling vibratory pressure of large amplitude in the fluid in the annulus. Scharton and Taylor(28) described a method of removing iron oxide corrosion

15 products and other scaling deposits from the pipes of steam generators using a combination of high power sound and a high-temperature solvent (e.g., sodium EDTA, citric acid and a corrosion inhibitor). The acoustic transducers operated in the frequency range 2-200 kHz and generated an output acoustic power

20 greater than 0.2 W/cm^2, a value which is above the cavitation threshold of aerated water at ambient pressure and temperature(29). The transducers were located permanently on the outside of the heat exchanger tubes. De Witz and Yeager(30) described an ultrasonic method to clean the fouled

25 surfaces of submerged structures, such as the hulls of ships. The ultrasonic cleaner consisted of two ultrasonic transducers focussed on a small area of surface to be cleaned. The transducers operated at slightly different frequencies, typically in the range 180-210 kHz; no details were disclosed on

30 the acoustic power required to clean the fouled surfaces. D'Arcy et al.(31) disclosed a method of cleaning underwater structures to depths of up to 1000 metres using focussed ultrasound in the frequency range 40-100 kHz. The ultrasound was generated and focussed using an array of transducers located on the concave

35 surface of a spherical cap. The density of acoustic power at the

focal point of the array of transducers was stated to be about 500 W/cm^2, a value that is approximately 3 orders of magnitude above the cavitation threshold of water at ambient pressure. D'Arcy et al. suggested the high power acoustic array could b

5 used to clean the base of oil production platforms. Pechkov et al.(32) disclosed the design of a high power acoustic logging tool to stimulate fluid production from oil wells. The acoustic power was provided by pulsed magnetostrictive transducers operating in the frequency range 5-30 kHz and emitting an

10 acoustic power density of up to 1 W/cm^2. The tool was designed to give a stand-off from the treated formation of 0.2-0.5λ, where λ is the wavelength of the sound in the borehole fluid. The treated formations were exposed to the acoustic power for periods of 5-60 minutes. Pechkov et al. claimed that the applied

15 ultrasound reduced the viscosity of the fluid in permeable formations and fluidised the particulate matter, thus facilitating its removal.

Gollapudi et al.(33) showed that ultrasound applied at a

20 frequency of 10 kHz could remove asphaltene deposits from a sand pack saturated with both water and kerosene at ambient pressure. Although the acoustic power applied to the sand packs during cleaning was not measured, the ultrasonic transducer could generate a maximum output acoustical power of 250 W. The authors

25 discussed the role of acoustic cavitation in the cleaning process and acoustic cavitation was undoubtedly achieved at the power settings reported. The asphaltene deposits were observed to be removed significantly more efficiently by the ultrasound in kerosene than in water. Venkitaraman et al.(34) have

30 demonstrated under laboratory conditions that the damage caused to permeable formation by the invasion of clay particles from drilling fluids can be partially removed by the application of high power ultrasound. Two ultrasonic transducers were used; one was a high power ultrasonic horn operating at a frequency of 20

35 kHz with an output power of up to 250 W and the other was a low

power transducer operating over frequency range 10-100 kHz. Th
same authors subsequently evaluated the application of high
power ultrasound under laboratory conditions for the removal of
organic deposits and formation damage caused by the invasion of
5 drilling fluid filtrate containing water-soluble polymers(35).
Using the same ultrasonic transducers, it was demonstrated that
polymer-induced formation damage was considerably more difficult
to remove than the damage caused by clay fines. However,
formation damage resulting from the precipitation of wax in the
10 test core samples could be removed by sonication when the core
samples were soaked in a suitable solvent.

Maki and Sharma(36) have described the use of a general purpose
acoustic cleaning tool for improving the near wellbore
15 permeability of producing formations by redissolving or
resuspending restricting materials. The cleaning tool was
reported to generate acoustic power densities of up to 2 W/cm^2,
which is above the cavitation threshold for water at ambient
temperature and pressure(27). The tool, which consisted of an
20 array of air-backed high power acoustic transducers of the type
described by Widener(37), was designed to be deployed into the
well on a wireline cable. The transducers described by Widener
would be expected to operate in the frequency range 10-100 kHz.
Auzerais and Liang(38) have used high power ultrasound to remove
25 the filter cake formed by the drilling fluid during the drilling
of a well in order to measure the pressure in permeable
formations. The high power ultrasound was generated by a
focussing transducer operating in the frequency range 100-500
kHz and capable of operating at a peak input power of up to 1
30 kW. Patzner(39) has described an ultrasonic tool for cleaning
producing wells. The wireline-deployable tool consisted of an
array of magnetostrictive transducers operating in the frequency
range 18-25 kHz (preferably at 20 kHz) and emitting an acoustic
power density in the range 8-12 W/cm^2. The tool was also equipped
35 with a pump to remove the debris of the fouling deposits

disaggregated by the ultrasonic tool. McNeal(40) disclosed a method to prevent the fouling of ships and other marine structures by the use of ultrasound over the frequency range 20-60 kHz. One demonstration of the invention was the location of

5   a number of ultrasonic transducers on the hull of a ship over a period of 4 months. Over this time period the transducers, which were powered intermittently, gave effective relief from marine fouling. McNeal revealed no details of the power consumption of the transducers, but one embodiment of the invention consisted

10   of the array being powered by a 9 volt battery. Piedrahita and Wong(41) have used high power ultrasound to prevent biofouling of chemical sensors used in aquatic environments. The ultrasound was generated by a transducer operating in the frequency range 10-100 kHz and yielding a sufficient power density (> 0.1-1

15   W/cm^2) to drive acoustic cavitation. Piedrahita and Wong used the acoustic cleaning technique to maintain the performance of a dissolved oxygen sensor located in microbiologically active water for seven days. The transducer was located over the range 4-10 mm from the active membrane of the oxygen sensor and

20   activated for a time period of 6-90 seconds over a time interval of 5-120 minutes.

Several papers and patents have reported on the use of high power ultrasound to accelerate the dissolution of scale by

25   chemical scale dissolvers applied in pipelines and producing oil wells. Paul and Morris(42) have claimed the use of low frequency (1.5-6.5 kHz) sonic energy to accelerate the dissolution of alkaline earth metal scales using scale dissolving solutions (typically containing the chelating agents EDTA or DTPA).

30   Gunarathne and Keatch(10,11) have shown that the application of low-power ultrasound can increase the rate of dissolution of barium sulphate scale using commercially available scale dissolvers; the power density was claimed to be below that required to cavitate the scale dissolving solution.

35

In conclusion, there appears to be no prior art describing either an acoustic scale sensor or an acoustic cleaning device located permanently or quasi-permanently in a well producing hydrocarbons. There appears to be no prior art of any
5 description for the concept of a sensor for hydrocarbon wells to monitor the formation of inorganic or organic scales, biofouling or corrosion and initiate a cleaning action.

SUMMARY OF THE INVENTION
10

Regarding a first aspect of the invention , there is provided a wellbore apparatus, comprising a) an installation permanently or quasi-permanently located in a wellbore, said installation having a surface directly exposed to wellbore fluids; (b) a
15 deposit monitor permanently or quasi-permanently located in a wellbore said monitor being adapted to measure deposition of material onto said surface; (c) a power supply adapted to supply said monitor with electrical energy; and (d) a deposit removal
20 system for at least partially removing said deposition from said surface, said deposit removal system being in a control loop with said deposit monitor.

In a preferred embodiment the deposit monitor is a high power
25 ultrasonic transducer coupled to an acoustic horn for measuring the deposition of the organic and inorganic scales that form from the fluids produced in hydrocarbon wells.

The transducer is preferably designed to operate in the
30 frequency range 10-150 kHz with a maximum acoustical power outputs of 10-500 W. The maximum power is only required during the cleaning process for less than 10 seconds or even less than 1 second. The optimal frequency range is believed to lie within the range of 50 to 100 kHz. It was found that higher

frequencies, particularly frequencies in the MHz region, are not applicable for permanent downhole deployment.

5   The growth of wellbore deposits is monitored by the decrease in the resonant frequency of the transducer with increasing thickness of deposit. The resonant frequency is conveniently determined from the real part of the admittance spectrum of the transducer. The horn amplifies the effect of the scale deposit on the measured admittance of the transducer.

10

The term "horn" is used as generic expression for a tapering end piece mounted onto the body of the acoustic transducer. The horn can be bolted or glued to the body of the transducer material. The length of the horn is preferably some integer multiple of
15   half the wavelength of the acoustic wave generated. The tapering can be achieved by cutting steps into the material or smoothly, e.g., as exponential tapering.

The horn material can be chosen arbitrarily from a large variety
20   of solid materials. It is however a preferred feature of the invention to have the horn tip made of a material that matches the properties of the surrounding material, so as to ensure that the deposits on the surrounding material are accurately measured.
25

At least the tip of the horn is directly exposed to the wellbore fluid causing the deposition.

The transducer is able to detect inorganic deposits or scales,
30   such as barium sulphate or calcium and organic deposits, such as waxes, at a thickness of approximately 100 μm.

Scales can be removed from the transducer by operation at high power; the transducer is therefore able both to detect and clean
35   deposits. The ultrasonic transducer is also able to clean scale

from the surfaces of other components used in producing
hydrocarbon wells, such as those made of glass, metal or
plastics. The acoustic transducers can be permanently located in
producing hydrocarbon wells and indicate the location and rate
5 of scale deposition. The measurement of scale deposition can be
used to direct scale treatment procedures, such as the placement
of inhibitors or the application of scale dissolvers, and to
warn of scale accumulation on critical downhole production
equipment, such as chokes and sliding sleeves. The acoustic
10 scale sensor can also be used to determine the effectiveness of
any treatment to remove scale or other wellbore deposits.

The control loop comprises either be a suitably programmed
microprocessor or computer executing pre-programmed tasks. Or,
15 it could include visual display units allowing a human operator
to make decisions based on the measurements provided by the
deposit monitor.

Permanently or quasi-permanently installed in a wellbore or
20 below the surface of the Earth refers to installation that are
fixed to the wellbore and thus can be retrieved to the surface
only under great costs and even sacrifice of equipment.

These and other features of the invention, preferred embodiments
25 and variants thereof, possible applications and advantages will
become appreciated and understood by those skilled in the art
from the following detailed description and drawings.

30

35

DRAWINGS

FIGs. 1A-C   are schematic illustrations of acoustic devices suitable for implementing the invention;

5

FIG. 2A   shows the resonant frequencies of an acoustic devices shown in FIG. 1B as measured by the real part of the admittance in air, water and kerosene;

10   FIG. 2B   shows an enlarged part of FIG 2B;

FIG. 3   illustrates the shift of the resonant frequency with increasing scale deposition;

15   FIG. 4   illustrates the shift of the resonant frequency with increasing wax deposition;

FIG. 5   illustrates the shift of the resonant frequency after cleaning the tip of a sensor;

20

FIG. 6   illustrates the power supply used to remove deposits from a surface exposed to wellbore fluids;

FIG. 7   illustrates a downhole installation in accordance with the invention;

25

FIG. 8   illustrates a sensor installation with self-cleaning equipment in accordance with the invention;

30   FIGs. 9A,B   illustrate further sensor installations with self-cleaning equipment in accordance with the invention; and

FIG. 9C   shows a schematic sensor adapted to further analyse wellbore deposits.

35

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MODE(S) FOR CARRYING OUT THE INVENTION

(I) ACOUSTIC SCALE/DEPOSITS SENSOR

5
The scale (or deposits) sensor consists of an ultrasonic piezoelectric transducer coupled to a suitable metal horn. The resulting ultrasonic device is characterised by a sharp resonant frequency, which can be conveniently determined by the

10 measurement of the admittance (or impedance) spectrum of the device. The resonance frequency is sensitive to any solid deposit that forms on the tip of the horn and the magnitude of the frequency shift is a measure of the mass loading. These ultrasonic transducers typically operate in the frequency range

15 10-100 kHz and can deliver high levels of acoustic power, typically in the range 1-500 W, when driven by a high input alternating voltage at its resonant frequency.

FIG. 1 shows schematics of several types of ultrasonic

20 transducer attached to an acoustic horn. The basic elements of the scale deposit sensor 10 are a transducer 11 made of piezoelectric material, a power supply with electrodes 12 to cause oscillations of the transducer, and a horn 13. The horn is made of aluminum. The working surface of the transducer 131, on

25 which the deposition of the scale is sensed, is the tip of the horn. In a downhole installation, the tip 131 will exposed to wellbore fluids and accumulate deposits.

The resonant frequency of the acoustic device is determined by

30 the size of the piezoelectric and the attached horn and the materials from which the piezoelectric and metal horn are constructed. The variants differ in their respective horn design. The horn 13 shown in FIG. 1A has a stepwise tapering. In FIG. 1B, the tapering is smooth with an exponentially reducing

35 diameter of the horn 14. The horn coupled to the ultrasonic

piezoelectric transducer was made of aluminium. The resulting device had a sharp resonant frequency in air of 40 kHz nominally and the area of the horn tip was 0.2 cm² . In FIG. 1C, the tapering is degenerated to a single step giving the horn 15 a
5 pin-like shape.

Further indicated in FIG. 1 is the length of the horn as integer multiple N of half the wavelength ($\lambda/2$) of the acoustic wave generated by the transducer.
10

Table 1 shows the resonant frequency of each ultrasonic horn and the width of the resonance at half peak height. The peak width of the resonance is typically 1-2% of the resonant frequency.

15

Table 1. Resonant frequencies in air of the ultrasonic transducers shown in FIG. 1.

Transducer type in FIG. 1	Resonant frequency (kHz)	Width of resonance at half peak height (Hz)
a	19.86	
b	39.04	21
c	54.63	52
		96

20

FIG. 2 shows the resonant frequency of the acoustic sensor shown in FIG. 1B as measured by the real part of the admittance in Siemens (S).The resonant frequency of the ultrasonic transducer
25 is modified by the nature of the fluid in which it is immersed. FIG. 2 compares the resonant frequency of the ultrasonic transducer immersed in air, water and kerosene. The resonance frequency of the transducer decreases when the metal horn is immersed in a denser fluid and the resonance broadens with more

viscous fluids. The fine structure (shown in FIG. 2B) on the admittance spectra measured when the transducer is immersed in water and kerosene at ambient pressure is caused by the attachment of small air bubbles to the horn.

5

FIG. 3 shows the shift in the resonant frequency of a transducer and metal horn with thickness of attached scale when the horn is immersed in water in a pressure vessel at a hydrostatic pressure of 4000 psi (270 bar). The resonant frequency of the 20 kHz

10 transducer shifts by 85 Hz per millimetre of scale of density 4.50 g/cm^3.

Further measurements show the variation of the shift in the resonance frequency of a 40 kHz transducer as a function of

15 scale thickness in water at ambient pressure for two scale types with densities of 2.75 and 4.50 g/cm^3. The resonant frequency of the transducer decreases by 774 Hz per millimetre of scale of density $\rho=2.75$ g/cm^3 and 966 Hz per millimetre of scale of density $\rho=4.50$ g/cm^3.

20

The accumulation of inorganic scale can also be detected by a shift in the resonant frequency of a transducer when the horn is immersed in a liquid hydrocarbon. When comparing the admittance spectra of a 40 kHz transducer and horn immersed in kerosene at

25 ambient pressure with and without inorganic scale attached, it was found that the shift in the resonant frequency of the transducer is 1317 Hz per millimetre of scale of density $\rho=4.50$ g/cm^3 in kerosene at ambient pressure.

30 The resonant frequency of an ultrasonic transducer and horn also decreases when organic deposits, such as wax, form on the tip of the horn. FIG. 4 shows the admittance spectra of a 40 kHz ultrasonic transducer and metal horn immersed in water at ambient pressure with wax of various thicknesses attached to the

35 tip of the horn. The resonant frequency of the transducer

decreases by 180 Hz per millimetre of wax of density 0.79 g/cm^3 when the horn is immersed in water at ambient pressure.

(II) ACOUSTIC SCALE/DEPOSITS CLEANING

5

The inorganic and organic deposits that accumulate on the tip of the horn can be removed by applying a high alternating voltage to the transducer. The strain produced in the transducer and the attached horn breaks the bond between the horn tip and the

10 deposit and the tip is cleaned. The acoustic deposits sensor can therefore be self-cleaning. The acoustic scale/deposits sensor is also able to clean scale from the surfaces of other components, which are either in close proximity to the tip of the horn or incorporated into it.

15

The scale was deposited on the tip of a metal horn connected to a 20 kHz ultrasonic transducer. The horn and transducer were housed in the cap of a cell that can be pressurised to 340 bar (5000 psi). The area of the horn tip is 2.87 cm^2, the average

20 scale thickness is 1.47 mm and the scale density is 4.50 g/cm^3. A high voltage was applied to the transducer and the horn was sonicated in a pressure cell at a hydrostatic pressure of 136 bar (2000 psi). All of the inorganic scale was removed from the tip of the horn.

25

FIG. 5 compares the admittance spectra of the acoustic transducer and metal horn before and after acoustic cleaning at 136 bar (2000 psi). The resonant frequency of the ultrasonic transducer and metal horn changed by 210 Hz after sonication.

30

The electrical power that is required by the transducer to remove the scale from the tip of the horn can be determined from the input voltage and current. The frequency of the input voltage and current is 19.84 kHz, which compares to a value of

35 19.81 kHz obtained from the admittance spectrum of the cleaned

horn. The scale, which consisted of a deposit with a density of 4.50 g/cm^3 and a thickness of 1.47 mm, was removed from the metal horn at a hydrostatic pressure of 136 bar (2000 psi). FIG. 6 shows the input power waveform supplied to the transducer during

5   the cleaning of the scale. The modulus of the time-averaged input electrical power of the waveform shown in FIG. 6 is 20.4 W.

(III) SOME APPLICATIONS OF AN ACOUSTIC DEPOSITS SENSOR AND

10   CLEANER

(a) Permanent Scale/Deposits Monitor. Ultrasonic transducers, of the type described above, operating over a range of frequencies, typically 10-150 kHz, can be permanently installed in a

15   producing hydrocarbon well to determine the rate of accumulation of scale and other deposits (wax, asphaltene, etc.). The transducers can be deployed at various locations in the well, including surface production pipes, in order to determine the location of scale formation. The transducers can be used to

20   determine the rate of accumulation of scale and other deposits and these measurements can be used to select the appropriate treatment to maintain the productivity of the well, such as the deployment of scale inhibitors or scale dissolvers. The deposits accumulated on the horn attached to the transducer can be

25   cleaned periodically to maintain its sensitivity.

(b) Maintenance of Intelligent Completions. More specifically, the ultrasonic sensor can be used to determine the accumulation of scale, wax or asphaltene on critical downhole equipment, such

30   as chokes, valves and the sliding sleeves on intelligent completion systems. The measurements can be used to select an appropriate treatment to maintain the integrity and operation of the equipment, e.g., deployment of a scale dissolver to remove scale from critical components.

35

In FIG. 7 reference is made to an "intelligent" completion system deployed to control the flow of wellbore fluid into a production pipe.

5   FIG. 7 shows a schematic of part of an intelligent completion system. An intelligent completion allows active control of downhole processes such as flow rate measurements and control. A wellbore **70** is shown with a casing **701** installed. At certain locations the casing **701** is perforated by holes 702 to allow
10   wellbore fluid to enter the wellbore. Installed within the wellbore is a production pipe **71** with a slotted section **711**. Wellbore fluid enters the production pipe via the slotted section **711**. Mounted within the production pipe is a sliding sleeve **712**. The sliding sleeve **712** controls the flow of
15   reservoir fluids into the production tubing from a particular section of the well. The flow rate, pressure and temperature of the production fluids are measured by a sensor sub **713** near the slotted section **711** into the tubing. The sliding sleeve **712** is operated by a downhole electrical motor **714** that is powered by
20   means of an electrical cable **721** from the surface **72**.

One problem associated with the use of a sliding sleeve is the formation of wellbore deposits, such as inorganic scale or wax, on the sleeve or its track. It is common practice to design the
25   completion hardware such that the electric motor **714** is sufficiently powerful to remove small amounts of scale when the sleeve is moved. However, attempting to remove scale or other deposits by scraping with the sleeve **712** may result in damage to the track and possible jamming. The location of an acoustic
30   scale sensor **715** close to the sliding sleeve **712** will enable the accumulation of deposits on completion hardware to be assessed through control equipment **722** located at the surface quantitatively. Transfer of energy and data signal between control equipment **722** and the sensor **715** is done via wiring **716**

run with the production tubing. If scale accumulation on the sleeve is considered to be above a level at which it can be safely operated, then an external scale removal process may be required (e.g., application of a scale dissolver solution).

5   Alternatively, the control equipment **722** could be used to activate the sleeve periodically or responsive to a threshold amount of deposit as measured by the scale sensor **715**. In yet another alternative the control equipment **722** could at least partly be incorporated into the downhole installation. By thus

10 providing a direct feedback control between sleeve and deposit monitor **715**, the amount of intervention from the surface can be reduced.

(c) Acoustic Cleaning of Scale and Other Deposits. The

15 ultrasonic transducer and associated horn can be used to remove scale and other deposits (wax, asphaltene, etc.) from critical components that are used in wellbore measurement devices and exposed to wellbore fluids. The components can be part of measurement systems that are either permanently installed in

20 producing hydrocarbon wells or temporarily exposed to the fluids produced by the hydrocarbon well, e.g., on a wireline-deployable tool. Critical components exposed to wellbore fluids that may require cleaning include separation membranes, optical windows and electrical contacts such as electrodes.

25

FIG. 8 refers to a venturi-type flowmeter having a gamma-ray sensor in its constriction section.

It shows a schematic of a gradio-venturi tube **81** located in the

30 tubing **80** of a producing hydrocarbon well. Located within the constriction formed by the venturi 81 is a gamma ray sensor **82**. Details of those known components of a gradio-venturi can be found for example in U.S Patent No. 5,591,922. The gamma ray sensor, which consists of a gamma ray source **821** (frequently a

35 dual energy source) and a gamma ray detector **822**, such as a

photomultiplier tube. The gamma rays enter and leave the tube by means of nuclear windows **823** made of a material such as boron carbide. Gamma-ray devices as described above are known as such and described for example in the U.K. Patent Application No.

5   9919271.8.

A significant problem faced by the gamma ray density measurement is the accumulation of inorganic or organic scales on the nuclear windows **823**. For example, the accumulation of small

10 amounts of barium sulphate (barite) scale may result in a serious overestimate of the density of the production fluids. Similarly, the accumulation of radioactive scales on the nuclear windows may give rise to erroneous measurements. The accumulation of organic scales, such as asphaltenes that may

15 contain elements with of high atomic number, can also corrupt the density measurement.

One solution to the problem of deposits accumulation on the nuclear windows **823** is to incorporate them into a high power

20 ultrasonic transducer and horn as is the subject of the present invention (see FIG. 1 above). FIG. 8 shows the two windows located in a hollow horn **824** and transducer **825**; the windows **823** are cleaned by operating the transducer in its high power mode. The accumulation of deposits on the windows can be measured by a

25 shift in the resonance frequency of the transducer and horn, as described above.

The gradio-venturi tube of the type above can be located either on the surface or downhole, e.g., as part of an intelligent

30 completion system.

FIG. 9 shows further examples of the use of an ultrasonic transducer and horn to clean measurement devices that may be deployed in a producing hydrocarbon well or at surface

35 installation monitoring the flow of hydrocarbon from the well.

FIG. 9A shows a schematic of an optical window **931** located at the tip of a horn **93** attached to an ultrasonic transducer **91**. The optical window **931**, which can be made of a suitably

5 resistant material such as diamond or sapphire, can be connected to a source and detector using an optical fibre **95** or other optical conduit such as a light pipe. The optical transmission of the window can be maintained by removing deposits of organic and inorganic scales with ultrasonic cleaning. The accumulation

10 of deposits on the optical window can be determined by either the decreased transmissivity of the window or the change in the admittance spectrum of the transducer **91** and horn **93** assembly.

FIG. 9B shows a schematic of an ultrasonic transducer **91** and

15 horn **94** used to clean the membrane **961** of an ion selective electrode **96** that could be used to measure the activity of an ionic species in the water produced from a hydrocarbon well. The performance of the membrane **961** is maintained by the cleaning action of the ultrasonic transducer **91** and horn **94**, which are in

20 close proximity to the membrane. The ultrasonic cleaning technique can be used to maintain the permeability of membranes used to separate various components from the fluids produced from hydrocarbon wells, e.g., gas extraction membranes, oil-water separation membranes. Note that a separation membrane and

25 electrode can also be incorporated into the horn coupled to a transducer.

(d) Identification of Scale Type. The resonant frequency of the transducer and horn responds to the mass of the attached

30 deposits and it may not be possible to identify the type of scale deposit in the absence of other measurements. One of a variety of measurements could be used to identify the type of scale deposit accumulated on the acoustic horn and thus enable acoustic scale sensor to measure the thickness of the deposit.

35 Two examples are give. Firstly, a spectroscopic measurement

could be employed, using an optical widow of the design shown in FIG. 9A. The scale type can identified by a total internal reflection spectroscopic technique, such as infrared spectroscopy, or Raman spectroscopy, which, as reflection and

5   scattering techniques, are insensitive to the thickness of the scale layer. A second possible technique is to use a second acoustic sensor, embedded in the acoustic horn, to measure the acoustic transit time through the scale deposit.

10   FIG. 10 shows a schematic of the acoustic sensor used to measure the acoustic transit time ΔT_t through the scale film. Pulsed ultrasound is emitted from an emitting transducer **981** and the reflections are collected by a second receiving transducer **982**. The acoustic impedance Z of the scale layer **99** can be estimated

15   by the measured values of the mass W of scale attached to the acoustic horn **97** and ΔT_t. The thickness of scale h attached to the horn is related to W by

[1]
$$h = \frac{W}{\rho_s A}$$

20   where ρ_s is the density of the scale and A is the area of the tip of the horn. The thickness h is related to ΔT_t by

[2]
$$h = \frac{\Delta T_t V}{2} ,$$

25   where V is the velocity of sound in the scale layer. The combination of eqn.[1] and [2] gives

[3]
$$Z = \rho_s V = \frac{2W}{\Delta T_t A} .$$

30   The scale type can be discriminated by the measured value of Z. Table 4 shows the values of the acoustic impedance Z as a

function of scale type. When Z is identified the thickness h of th scale deposit can be calculated using eqns. [1] or [2] using the known values of V and ρ_s.

5

Table 4. Values of the acoustic impedance Z for various inorganic scales.

Scale type	Acoustic impedance Z (kg/m^{2}s x 10^{-6})
calcite	17.6
anhydrite	18.0
celestite	19.1
barite	19.9

10 (e) Monitoring Scale/Deposits Removal Techniques. The acoustic scale sensor can be used to evaluate the efficiency of an external scale removal treatment process, such as a scale dissolver solution or a physical scale removal technique. The scale removal treatment can be monitored in real time using the

15 change in the resonant frequency of the transducer and horn. The acoustic scale monitor can therefore be used as part of a scale maintenance service that monitors scale accumulation and evaluates the cleaning/removal process.

20 (f) Fluid Composition and Pressure Effects. The resonant frequency of the ultrasonic transducer and horn with no deposits attached depends on the composition of the fluid with which it is in contact and its hydrostatic pressure. A change in the composition of the produced fluid or its hydrostatic pressure

25 may therefore obscure the change in resonant frequency due to the accumulation of inorganic or organic deposits. A change in resonant frequency due to a change in fluid properties can be measured using a second matched transducer and horn, which is in close proximity to the scale detector. The second transducer is

30 cleaned frequently to ensure that the horn is always free from

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inorganic and organic scales and that the changes in its resonant frequency are solely caused by changes in fluid composition and pressure.

5 (g) Surface Modification of Acoustic Horn. An important aspect of a scale/deposits sensor permanently installed in a producing hydrocarbon well is that the rate of accumulation of deposits must be the same as that of the region of the wellbore it is monitoring. The composition and morphology of the surface of the

10 tip of the horn must be such as to give the same rate of scale accumulation as the solid surfaces in the close environs of the sensor. The surface of the horn tip must be suitably controlled by the choice of material and/or coating. The material and coating used to fabricate the horn must be able to withstand

15 repeated sonication.

(h) Size of Transducer and Horn. The size of an ultrasonic transducer and horn may be a critical issue for the permanent placement of such a device for scale/deposits monitoring. The

20 size of the transducer and horn are largely determined by the desired frequency of operation and the materials use to them. High power ultrasonic transducers and horns in the size range 5-6 cm, which operate in the frequency range 89-113 kHz, have been reported by Lal and White(43). The acoustic horns were

25 microfabricated from silicon wafers.

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CLAIMS

1.   A wellbore apparatus, comprising
     (a) an installation permanently or quasi-permanently
     located in a wellbore, said installation having a surface
     directly exposed to wellbore fluids;
     (b) a deposit monitor permanently or quasi-permanently
     located in a wellbore said monitor being adapted to
     measure deposition of material onto said surface;
     (c) a power supply adapted to supply said monitor with
     electrical energy; and
     (d) a deposit removal system for at least partially
     removing said deposition from said surface, said deposit
     removal system being in a control loop with said deposit
     monitor.

2.   The apparatus of claim 1, wherein the deposit monitor
     comprises a sensing element in direct contact with
     wellbore fluids.

3.   The apparatus of claim 2, wherein the deposit monitor
     comprises an acoustic transducer.

4.   The apparatus of claim 3, wherein the transducer is
     coupled to a focussing element.

5.   The apparatus of claim 3, wherein the transducer is
     coupled to an acoustic horn.

6.   The apparatus of claim 3, wherein the transducer adapted
     to measure the deposition as a shift of its resonance
     frequency.

7.   The apparatus of claim 6, wherein the resonance frequency
     of the monitor is in the range of 10 kHz to 150 kHz.

8.   The apparatus of claim 1, wherein the installation is selected from a group comprising switches, valves, sleeves, mandrels, and sensors.

5

9.   The apparatus of claim 1, wherein the cleaning system includes a deposition inhibiting or removing chemical agent.

10   10.   The apparatus of claim 1, wherein the cleaning system includes elements adapted to exert a physical force onto the deposits.

11.   The apparatus of claim 1, wherein the installation
15   comprises a sensor having an element exposed to the wellbore fluids and a deposition removal system adjacent to said element and adapted to remove deposits from said sensor element.

20   12.   The apparatus of claim 11, wherein the sensor is selected from a group comprising optical sensors, electro-chemical sensors, or acoustic sensors.

13.   The apparatus of claim 11, wherein the sensor element
25   exposed to wellbore fluids is selected from a group comprising optical windows, membranes, or sensitive areas of acoustic sensors.

14.   A wellbore sensor, comprising
30   (a) an acoustic transducer permanently or quasi-permanently located in a wellbore,
       (b) an energy focussing element coupled to said transducer, said element having a surface directly exposed to wellbore fluids;

(c) a power supply adapted to supply said transducer wi⌐
electrical energy in a first mode being adapted to
measure shifts in the resonance frequency of said
transducer and a second mode providing sufficient energy
to said transducer and energy focussing element to remove
deposits from said surface.

15. The sensor of claim 14, wherein the transducer and the
focussing element are permanently or quasi-permanently
installed below the surface of the Earth.

16. The sensor of claim 14, wherein the focussing element is
an acoustic horn.

17. The sensor of claim 14, wherein the power supply provides
energy at approximately resonance frequency.

18. The sensor of claim 14, wherein the sensor includes an
additional sensing system to analyse deposits.

ABSTRACT

5   Described is a downhole apparatus for detecting and removing
    deposits from a surface exposed to wellbore fluids. The
    apparatus can control the rate of deposition and the deposition
    removal operations. The combination of detection apparatus and
    removal apparatus provides a downhole instrument with self-
    cleaning operation mode.

10

$N \times \lambda/2$

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131

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FIG. 1A

FIG. 1B

$N \times \lambda/2$

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141

12

$N \times \lambda/2$

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11

151

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FIG. 1C

FIG. 2A

FIG. 2B

FIG. 3

FIG. 4

57,357

FIG. 5

FIG. 6

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722

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716

715

713

711

702

702

712

714

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701

FIG. 7

FIG. 8

FIG. 9A

91

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931

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FIG. 9B

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941

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961

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92

FIG. 9C